

USING NEW SUBMILLIMETRE SURVEYS TO IDENTIFY THE EVOLUTIONARY STATUS OF HIGH-Z GALAXIES

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1. Why submillimetre surveys?

In this paper we briefly describe a ‘key’ survey at submm wavelengths which we are currently conducting to address some of the most important questions in cosmology - how, at what epoch and over what period of time did massive galaxies form at high-redshift?

The primary motivation for undertaking surveys of high- z galaxies at submm wavelengths is the expectation, which has still to be proved, that the most massive galaxies ($M_{\text{baryonic}} \geq 5 \times 10^{11} M_{\odot}$) form the majority of their stars in a relatively short ($< 1 \text{ Gyr}$), but extremely luminous phase at rest-frame FIR wavelengths and hence, at redshifts $z > 3$, at wavelengths in the atmospheric windows between $350\mu - 1300\mu$ which are accessible from the ground.

Throughout this paper we are referring to the *rest-frame* FIR emission when discussing the observed submm spectral energy distribution, and that all physical quantities are calculated assuming $H_0 = 50 \text{ kms}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

1.1. EVOLUTIONARY STATUS OF HIGH-Z GALAXIES

Submm and mm continuum observations offer a unique opportunity to determine some fundamental properties that provide a measure of the evolutionary status of high- z galaxies, but only after making the following assumptions:

(a) that emission at submm wavelengths is due to *optically-thin* thermal re-radiation from dust grains at temperatures of $T_{\text{rest}} \simeq 30 - 70 \text{ K}$, and is neither the optically-thin emission of a lower-frequency radio synchrotron component (*e.g.* B20902+34 Downes *et al.* 1996, Yun & Scoville - *priv. comm.*), or the optically-thick self-absorbed emission from a higher-frequency mid-IR synchrotron component (*e.g.* de Kool & Begelman 1989, Schlickeiser *et al.* 1991);

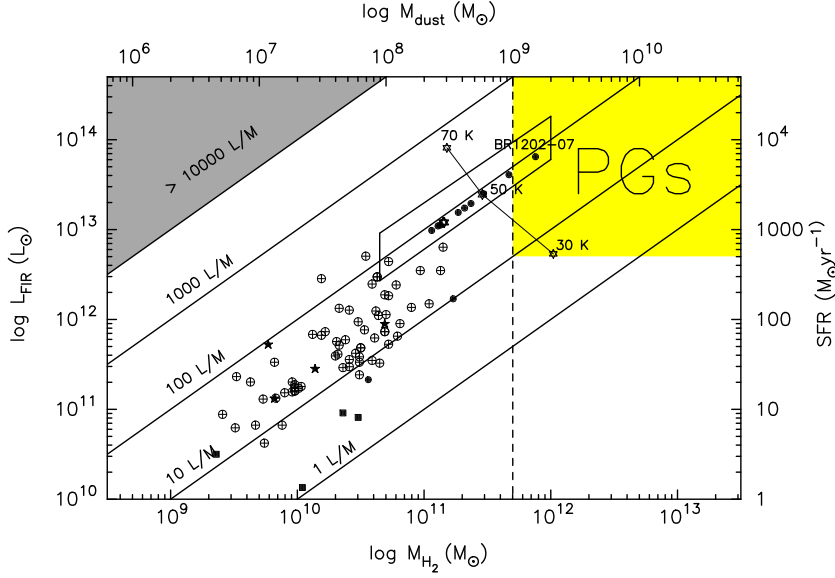


Figure 1. The physical properties of high- z radio galaxies (open stars) and radio-quiet quasars (filled circles), which lie within the parallelogram, have been derived from submm or mm continuum detections (assuming $T = 50$ K, $M_{H_2}/M_d = 500$) and are compared to those of starburst galaxies (filled stars), ULIRGs (crossed circles) and elliptical galaxies (filled squares) in the local universe. The diagonal lines indicate constant L_{FIR}/M_{H_2} . The vertical dashed-line shows the gas mass boundary, to the right of which is a region of the parameter space marked "PGs" where one can expect to find the progenitors of the most massive, $> 5 \times 10^{11} M_\odot$, elliptical galaxies. This figure is taken from Hughes, Dunlop & Rawlings (1997).

(b) that the thermal emission from dust grains at an observed temperature T_{obs} is due to a high- z target, where $T_{obs} = T_{rest}/(1+z)$, and is not confused with colder foreground galactic cirrus at 15 - 25 K;

(c) that within the high- z galaxy, the grains are heated by young, massive stars in active starforming regions, and not by emission from the associated AGN.

Given the above, it is possible to use the measured submm flux densities from high- z galaxies to estimate their rest-frame FIR luminosities, which are proportional to the starformation rate of massive stars at some early epoch. Additionally the remaining molecular gas mass available for future star-formation can be determined from a measure of the total dust mass, and compared to the expected baryonic mass in a present-day counterpart. For example observational evidence suggests that the most luminous host galaxies ($L \geq 5L_*$) of low- z quasars and radio galaxies have masses $\geq 5 \times 10^{11} M_\odot$ (Taylor *et al.* 1996), and thus we can describe the progenitors of similar galaxies forming around luminous high- z AGN

as *primæval* if they can be shown to contain a high gas content, comparable to the stellar mass in low- z quasars and radio galaxies, and to be undergoing an intense burst of starformation. The uncertainties in the dust temperature, grain models, gas/dust ratio and their consequences in the determination of the FIR luminosities, SFRs, and gas masses in high- z galaxies have been described in detail elsewhere by Hughes (1996) and Hughes, Dunlop & Rawlings (1997).

A summary of the physical properties of the few high- z radio galaxies and RQQs detected at submm and/or mm wavelengths is presented in fig.1. These properties are compared to those of the most luminous and active galaxies in the local universe. A conservative conclusion is that it is difficult, except possibly in the case of BR1202–0725 (although it may be lensed) to describe any of the high- z galaxies detected at submm and mm wavelengths as genuinely *primæval*, since they lie outside the region of parameter space where, according to our definition of $M_{H_2} > 5 \times 10^{11} M_\odot$ and a $SFR > 500 M_\odot \text{yr}^{-1}$, young galaxies should lie. Varying the assumed dust temperature through a reasonable range ($30K \rightarrow 70K$), as illustrated by the representative locus in fig.1, struggles to change this basic conclusion, but it does demonstrate the need to constrain the dust temperature which can only be achieved by making submm surveys at two or more wavelengths that straddle the rest-frame FIR peak at the highest redshifts (see §1.2).

1.2. TECHNICAL FEASIBILITY OF FUTURE SUBMM SURVEYS

It's all very well describing the importance of submm observations of high- z sources, but do the sensitivities of current and future instruments and telescopes make the detections of large numbers of high- z galaxies a realistic possibility? Such concerns are well justified given the extreme difficulty found in detecting only a handful of high- z AGN at submm wavelengths without the assistance of gravitational lensing (Dunlop *et al.* 1994, Ivison 1995, Isaak *et al.* 1994, Chini & Krügel 1994, McMahon *et al.* 1994, Cimatti & Freudling 1995, Hughes, Dunlop & Rawlings 1997, Omont *et al.* 1996).

In fig.2 we illustrate the dependence of flux density on redshift for a typical starburst galaxy SED in the major submm and mm atmospheric windows. The particular example shown is that of Arp 220 ($\log L_{FIR} \sim 12.3 L_\odot$, $SFR \sim 100 M_\odot \text{yr}^{-1}$), although the flux densities can be scaled for a starburst galaxy with any arbitrary luminosity or SFR at any redshift. The conclusion that can be drawn from fig.2 is that submm and mm instrumentation must achieve NEFD's of $< 30 \text{mJy Hz}^{-1/2}$, $< 80 \text{mJy Hz}^{-1/2}$, $< 250 \text{mJy Hz}^{-1/2}$ at 1.3 mm, $850\mu\text{m}$ and $450\mu\text{m}$ respectively if future studies are to detect, with reasonable integration times, high- z galaxies undergoing starformation at rates of $> 100 M_\odot \text{yr}^{-1}$. Such high and sustained SFRs are necessary if a massive galaxy, $\gg 10^{11} M_\odot$, is to be *built* in $< 1 \text{Gyr}$ - a timescale which, at high- z , corresponds to a redshift interval $\Delta z \sim 4.5 - 2.5$. These necessary instrumental sensitivities can be compared with those in table 1 for all the major existing (and proposed) submm telescopes. It is immediately clear that only the JCMT at $850\mu\text{m}$ and IRAM at 1.3mm currently provide sufficient sensitivity to carry out extensive cosmological studies, and that

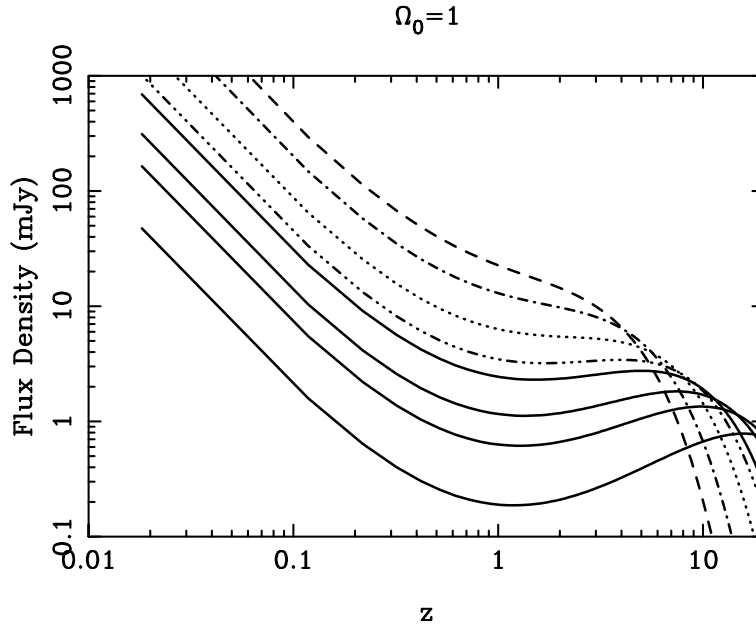


Figure 2. Each curve represents the dependence of flux density with redshift for a typical starburst galaxy spectrum at wavelengths of $350\mu\text{m}$, $450\mu\text{m}$, $600\mu\text{m}$, $750\mu\text{m}$, $850\mu\text{m}$, $1100\mu\text{m}$, $1300\mu\text{m}$ and $2000\mu\text{m}$, from top to bottom respectively. The curves are normalised to the flux density of Arp200 at $z=0.018$ with a FIR luminosity $L_{\text{FIR}} \simeq 2 \times 10^{12} L_{\odot}$ and a SFR $\sim 100 M_{\odot} \text{yr}^{-1}$.

further advances must await the future developments of the SMA, the South Pole 10-m project, FIRST and the ambitious large mm arrays (*e.g.* MMA and LMSA).

In addition to the gains in sensitivity, the availability of new instrumentation on ground-based telescopes (*e.g.* JCMT, IRAM) and satellites (ISO) gives rise to a combination of improved resolution, imaging capability and greater wavelength coverage in the FIR, submm and mm. Therefore it should soon be possible for the first time to properly test the validity of the assumptions outlined in §1.1, particularly quantifying the level of cirrus confusion on scales of $\sim 10''$, constraining the dust temperature, and discriminating between the competing thermal and non-thermal emission mechanisms in the FIR by measuring directly, and with high photometric precision, the rest-frame submm spectral indices of high- z galaxies (Chini *et al.* 1989, Hughes *et al.* 1993). Finally, since all massive galaxies at high- z have been originally identified by detecting a luminous AGN then the effect of the AGN continuum emission, through primary or secondary processes, on the FIR luminosity and on the overall evolution of the host galaxy must be quantified. This can be achieved by either detecting genuinely non-AGN galaxies, previously unidentified, in new submm blank field surveys, or by making pointed submm observations of samples covering a broad range of AGN luminosity and redshift. We describe the latter of these alternatives below.

TABLE 1. Continuum sensitivities of receivers on submm/mm telescopes. The SMA(6) NEFDs assume 6 antennae in the array; SMA(8) includes two additional Taiwanese antennae, and in parentheses the use of dual polarization heterodyne receivers at 345GHz. Numbers in italics are predicted sensitivities.

telescope	area (m ²)	NEFD (mJy Hz ^{-1/2})		
		1350 μ m	850 μ m	450 μ m
JCMT	177	60	80	700
CSO	79			2000
IRAM	707	60		
SEST	177	200		
SOFIA	5		<i>200</i>	<i>200</i>
SMA(6)	170	<i>102</i>	<i>238</i>	<i>2040</i>
SMA(8)+JCMT+CSO	481	<i>36</i>	<i>84 (59)</i>	<i>719</i>
South Pole 10-m	79		<i>50</i>	<i>60</i>
MMA	2010	<i>8</i>	<i>25</i>	<i>150</i>
FIRST	7		<i>54</i>	<i>54</i>

2. Submm observations of radio samples covering the P-z plane

We have chosen to address some of the questions of evolution and formation of massive galaxies by observing complete sub-samples of radio galaxies that span a factor of ~ 1000 in radio luminosity ($\log P_{408MHz} \sim 25.0 - 28.0 \text{ WHz}^{-1}\text{sr}^{-1}$) and range in redshift between $1 < z < 5$. The samples drawn from 3C, 6C, 7C and LBDS surveys are shown in fig. 3, and taken together eliminate the tight correlation between radio luminosity and redshift observed in any single survey by covering the entire P-z plane. It is well known that powerful low-z radio sources reside in elliptical galaxies and, assuming the same to be true at high-z, we can therefore study the gas mass fraction and level of star formation in massive host galaxies as a function of AGN luminosity at a particular redshift, and follow the evolution of these quantities over a period of $\sim 4\text{Gyr}$ (*i.e.* from $z \sim 5 \rightarrow 1$). We will report shortly on the first JCMT observations of these samples at 850 μ m and 450 μ m using the new bolometer array SCUBA.

3. Acknowledgements

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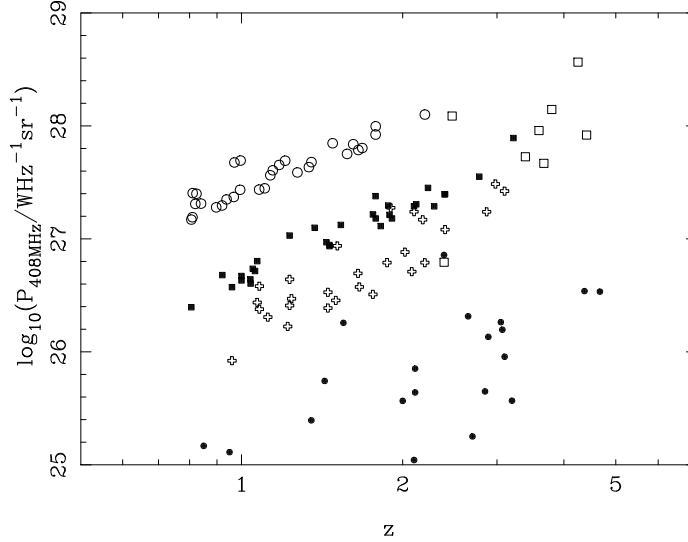


Figure 3. The radio-luminosity:redshift ($P-z$) plane of high- z galaxies selected from various radio surveys (3C - open circles; 6C - filled squares; 7C - crosses; LBDS - filled circles) to be observed at submm wavelengths. Using these samples we can quantify the contribution of an AGN to the rest-frame FIR luminosity, and trace the evolution of gas mass and star formation rate as function of redshift and radio luminosity.

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